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Runoff Simulation Using Radar Rainfall Data

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RUNOFF SIMULATION USING RADAR RAINFALL DATA[1]

John C. Peters and Daniel J. Easton[2]

ABSTRACT: Rainfall data products generated with the national network of WSR-88D radars are an important new data source provided by the National Weather Service. Radar-based data include rainfall depth on an hourly basis for grid cells that are nominally 4 km square. The availability of such data enables application of improved techniques for rainfall-runoff simulation. A simple quasi-distributed approach that applies a linear runoff transform to gridded rainfall excess has been developed. The approach is an adaptation of the Clark conceptual runoff model, which employs translation and linear storage. Data development for, and results of, an initial application to a 4160 km^2 watershed in the Midwestern U.S. are illustrated.
(KEY TERMS: hydrograph analysis and modeling; simulation; surface water hydrology; radar.)

INTRODUCTION

Traditional application of the unit hydrograph approach to runoff simulation involves the use of spatially averaged (lumped) values of basin rainfall and infiltration (losses). This approach has been of practical value because data available from typically sparse rain-gage networks are generally inadequate to justify more spatially detailed simulation methods. The availability of "new-generation" radar rainfall data enhances the attractiveness of distributed simulation approaches that take into account spatial variations of rainfall and watershed characteristics.

To facilitate initial use of radar rainfall data, a relatively simple quasi-distributed approach has been developed that applies a linear runoff transform to gridded rainfall excess. The approach is an adaptation of the Clark conceptual runoff model (Clark, 1943), which represents surface runoff with translation and linear-storage attenuation. In this adaptation, radar grid cells are superposed on the basin, and rainfall and losses are tracked uniquely for each cell. Rainfall excess for each cell is lagged to the basin outlet by the cell's travel time (i.e., time of travel from the cell to the basin outlet). The lagged excesses are routed through a linear reservoir, and baseflow is added to obtain a total-runoff hydrograph. The computer program that performs these computations is the Modified Clark (modClark) Runoff Simulation Program (HEC, 1995a).

RADAR RAINFALL DATA

A national network of WSR-88D (Weather Surveillance Radar-88 Doppler) radars is being deployed by the National Weather Service (NWS). Processing of precipitation data by the NWS is done in stages (Shedd and Fulton, 1993). Stage III products incorporate information from "ground truth" rain gages and satellite and surface temperature observations, and they result from merging ("mosaicking") data from overlapping radar coverages. For the application illustrated subsequently, Stage III hourly precipitation data were obtained via Internet from the NWS Arkansas-Red Basin River Forecast Center (ABRFC) in Tulsa, Oklahoma. As of mid-1995, the ABRFC was the only NWS River Forecast Center from which Stage III products were routinely available, although testing of Stage III processing was underway at several other River Forecast Centers.

The Stage III rainfall data are provided for cells defined by the Hydrologic Rainfall Analysis Project (HRAP) grid (Greene and Hudlow, 1982). The HRAP

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grid is uniform on a polar stereographic map projection. Consequently, the dimensions of an HRAP grid cell, as projected on the earth's surface, vary with latitude. Figure 1 illustrates an HRAP grid superposed over four subbasins of the 4160 km^2 Illinois River watershed upstream from Tenkiller Lake. The watershed is located in northeastern Oklahoma and northwestern Arkansas. The grid cell areas vary in this watershed from 16.3 to 16.5 km^2.

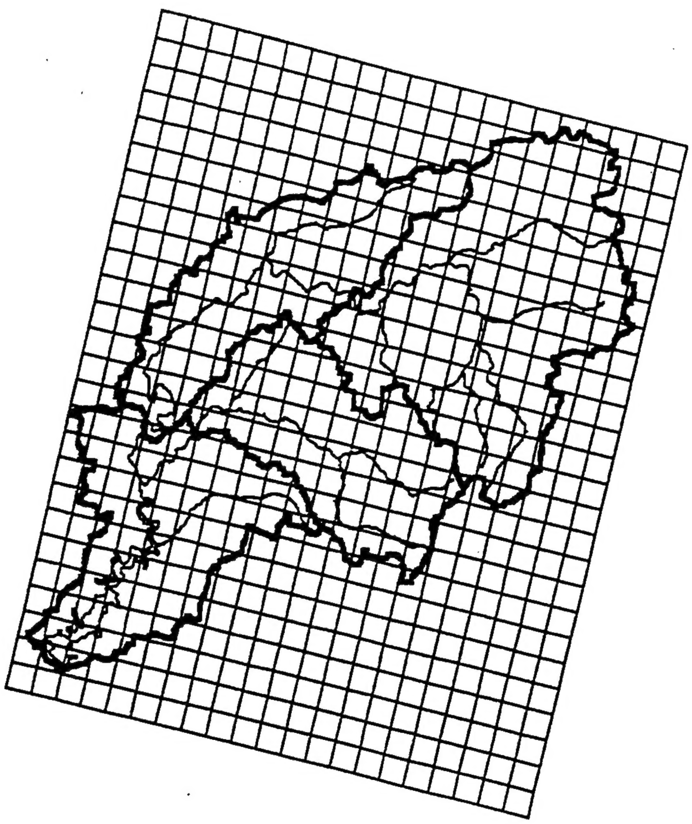

Figure 1. HRAP Grid Superposed on Four Subbasins of the Illinois River Watershed.

Radar rainfall data obtained from the ABRFC is in the netCDF (Network Common Data Form) format (Unidata Program Center, 1991). A utility program titled gridUtl (HEC, 1995b) loads the data into a direct access file associated with the Hydrologic Engineering Center's Data Storage System (HEC-DSS). The Modified Clark program retrieves the gridded rainfall data from an HEC-DSS file.

MODIFIED CLARK METHOD

Two basin parameters are required to transform rainfall excess to direct runoff with the Modified Clark method: time of concentration, T_c; and storage coefficient (for a linear reservoir), R. Both have units of time. Translation is performed on a grid cell basis by using a travel time index. The travel time (or translation lag) for a grid cell is calculated as follows:

$$(travel\ time)_{cell} = T_c \frac{(travel\ time\ index)_{cell}}{(travel\ time\ index)_{max}} \qquad (1)$$

where T_c is the time of concentration for the basin, $(travel\ time\ index)_{cell}$ is the travel time index for a cell, and $(travel\ time\ index)_{max}$ is the maximum travel time index of all of the cells associated with the basin. The development of a travel time index is described in the next section.

The lagged rainfall excess for each cell is routed through a linear reservoir with the following equation:

$$O_i = \left[\frac{\Delta t}{R + 0.5 * \Delta t}\right] I_{avg} + \left[1 - \frac{\Delta t}{R + 0.5 * \Delta t}\right] O_{i-1} \qquad (2)$$

where O_i is direct runoff at time i, R is the storage coefficient, I_{avg} is the average inflow for the interval i-1 to i, and Δt is the time interval.

CELL PARAMETERS

Part of the required input for the Modified Clark program is a cell-parameter file that contains the following information for each cell: cell x-coordinate, cell y-coordinate, area (within basin), and travel time index. As shown in the previous section, the travel time index for a cell is used to calculate a translation lag. The travel time from a cell to the basin outlet is

$$\tau = \frac{D}{V_{avg}} \qquad (3)$$

where τ is the time-of-travel to the basin outlet, D is the length of the flow path to the basin outlet, and V_{avg} is the average velocity over the flow path. If it is assumed that travel velocity is constant for the basin, then flow path length can serve as the cell travel time index.

An alternative to the assumption of a constant travel velocity is to incorporate a spatially distributed velocity field, as proposed by Maidment *et al.* (1996).

The travel velocity through a cell is assumed to be proportional to the cell slope and to the accumulated area of all cells contributing runoff to the cell. That is,

$$v_{cell} \propto S^a * A^b \tag{4}$$

where v_{cell} is the travel velocity through a cell, S is the cell slope, and A is the accumulated area of contributing cells. The accumulated area can be regarded as a surrogate for depth. A value of 0.5 has been found to be reasonable for both the a and b exponents (Maidment *et al.,* 1996). The travel time index for a cell is then defined as the integral of l_{cell}/v_{cell} along the flow path to the basin outlet, where l_{cell} is the length of flow path through a cell. Incorporation of a spatially distributed velocity field in computing travel time indices is worthy of further study. However, for the purposes of this paper, the assumption of a constant average velocity over all the basin flow paths is adopted for an initial demonstration of the Modified Clark method.

Procedures for using a geographic information system (GIS) to calculate cell areas and travel time indices have been developed (HEC, 1995c). The procedures require processing digital elevation model (DEM) data such as are available for the continental U.S. (via Internet) from the USGS EROS Data Center (USGS, 1990). An eight-direction "pour-point" algorithm defines the direction of flow from any grid cell to be in the direction of steepest descent from the cell to one of its eight neighbors. A flow path length is computed by summing the lengths of all segments along the path from the cell to the basin outlet. Area and travel time index are determined for DEM-based cells at a 100 m resolution. Radar cells (based on the HRAP grid) are then superposed and their areas and travel time indices are calculated by summing the areas and averaging the travel time indices of the encompassed DEM-based cells. The cell areas and travel time indices are treated as constants for a given basin. Thus GIS is used for a one-time processing of data and is not required for subsequent application of the Modified Clark program.

LOSSES, BASEFLOW, AND HYDROLOGIC ROUTING

Loss models available in the Modified Clark program are Initial/Constant, SCS Curve Number, and Green and Ampt. The methods are applied as in the HEC-1 program (HEC, 1990). The loss model parameters apply to all cells in the basin, but losses are calculated individually for each cell based on the rainfall intensities associated with that cell. Baseflow is modeled as in HEC-1. The starting flow, recession flow, and recession ratio parameters are used to calculate baseflow at the outlet of the basin.

The Modified Clark program can only simulate runoff from elemental basins – that is, basins that are not subdivided. However, the program has the capability to write its simulation results (i.e., discharge hydrographs) to the HEC-DSS. For applications with multi-subbasin watersheds, the hydrographs can be retrieved from HEC-DSS and routing performed with programs such as HEC-1, HEC1F (Peters and Ely, 1985), or UNET (HEC, 1993).

TEST WATERSHED

Runoff simulations were performed for the Illinois River watershed above Tenkiller Lake in northeastern Oklahoma and northwestern Arkansas. The 4,163 km^2 watershed was divided into four subbasins as shown in Figure 2. The subbasin areas and the number of radar cells in each subbasin are listed in Table 1. Stream gages are located at the outlets of subbasins 85, 86, and 113. Inflow to Tenkiller Lake can be computed from measured outflow and lake-level data. Figure 2 also shows the location of precipitation gages, for which hourly rainfall is available.

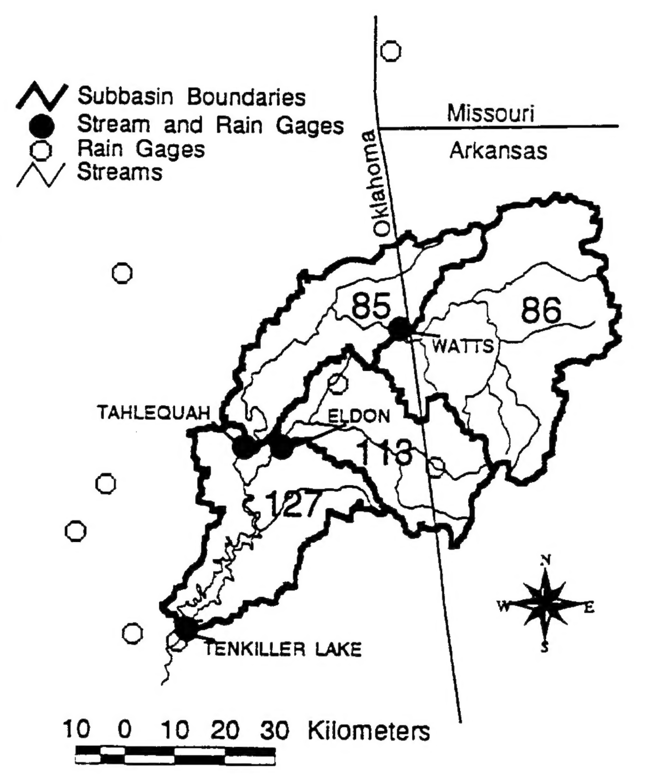

Figure 2. Illinois River Watershed.

TABLE 1. Subbasin Area and Number of Radar Cells.

Subbasin	Area (km^2)	Number of Radar Cells
85	829	84
86	1645	129
113	795	78
127	894	86

The watershed is in the Ozark Highlands and is heavily wooded. Elevations range from 140 meters above sea level at the outlet of Tenkiller Lake to 580 meters. The hills in the region are formed of porous limestone and overlain with cherty topsoil. The flood plains can be gravelly, and in places the substratum is too pervious to hold water. Therefore, high infiltration is expected (Soil Conservation Service, 1965 and 1970). For simplicity, the method of using an initial loss followed by a constant loss rate was adopted for calculating rainfall excess.

STORM EVENTS

Radar rainfall data for storms that occurred on November 4-5, 1994, January 13-14, 1995, and May 8, 1995, were used for the initial application of the Modified Clark method. Table 2 shows total average rainfall for each storm over the four subbasins as calculated using (a) Stage III radar data and (b) data from the precipitation gages shown in Figure 2. Total average rainfall from the gage data was calculated using an inverse distance-squared weighting procedure (HEC, 1989).

The total average precipitation calculated for each of the three storm events using gage data differs significantly from that calculated using radar data. Differences might be attributed to various factors, including the spatial variability of the rainfall, weighting of the gage data, the accuracy of the radar rainfall data, and associated processing procedures. While these are key issues with regard to rainfall measurement, their resolution is beyond the scope of this paper, which is intended to demonstrate use of the gridded rainfall data.

A time-area concentration histogram for subbasin 85 is shown in Figure 3. The histogram is based on the area and travel time index for each radar cell, and it shows the percent of the subbasin area that contributes runoff at the outlet (via translation) for increments of travel time (expressed as 10 percent increments of the time of concentration). A time-volume concentration histogram for the November 4-5, 1994, storm, which shows the percent of the total volume of rainfall that contributes runoff to the outlet for increments of travel time, is also shown in Figure 3. If the rainfall were distributed uniformly, the two histograms would be identical; the histograms differ because of spatial variations in rainfall. As shown, the time-volume histogram does not vary greatly from the time-area histogram. This was generally true for the three storm events over the Illinois River watershed. Conclusions about the time-space rainfall distribution cannot be made from these histograms because the hourly cell data have been integrated over time.

TABLE 2. Total Average Rainfall as Calculated Using Radar and Gage Rainfall Data.

Storm Event	Subbasin	Total Average Rainfall (radar) (mm)	Total Average Rainfall (gage) (mm)
November 4-5, 1994	85	93	74
November. 4-5, 1994	86	90	55
November 4-5, 1994	113	98	118
November 4-5, 1994	127	92	133
January 13-14, 1995	85	91	51
January 13-14, 1995	86	94	44
January 13-14, 1995	113	81	55
January 13-14, 1995	127	66	75
May 8, 1995	85	57	37
May 8, 1995	86	56	31
May 8, 1995	113	58	39
May 8, 1995	127	62	81

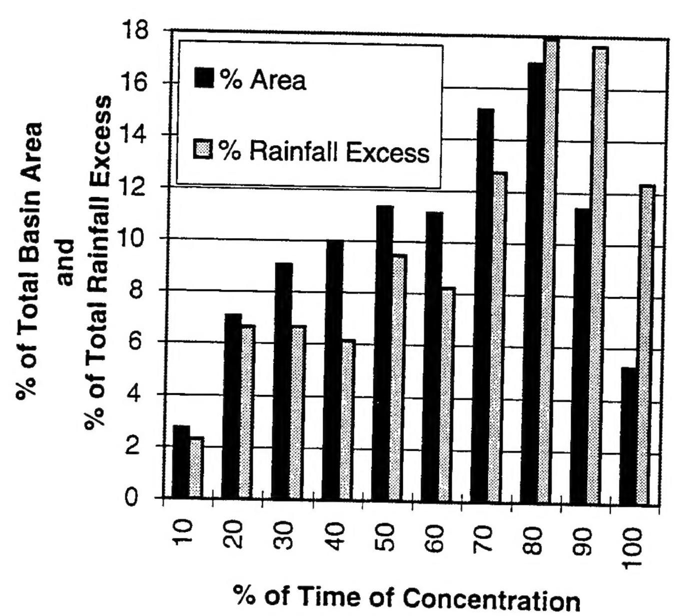

Figure 3. Time-Area and Time-Rainfall Volume Histograms for the November 4-5, 1994, Storm on Subbasin 85.

MODIFIED CLARK SIMULATION

Results of the Modified Clark runoff simulations at the Watts, Tahlequah, and Eldon gages and Tenkiller Lake for the November 4-5, 1994, January 13-14, 1995, and May 8, 1995, storms are shown in Figures 4, 5, and 6, respectively. Loss parameters were adjusted so that the volumes of observed and simulated runoff were essentially identical. The Clark (i.e., basin time-of-concentration and storage coefficient), loss, and baseflow parameters used in the simulations are shown in Table 3. Values for time-of-concentration and storage coefficient were kept constant for the simulations. Flow simulation at the Tahlequah gage station and Tenkiller Lake required stream routing of hydrographs generated at upstream locations. This was performed using the modified Puls method as implemented in HEC-1 (HEC, 1990) with storage-discharge criteria furnished by the Tulsa District of the Corps of Engineers.

As shown in Figures 4, 5, and 6, the simulated hydrographs provide a reasonable fit to the observed hydrographs. Simulations were also performed using spatially averaged radar-rainfall data. The results were similar to those based on grid-distributed rainfall. This is attributed to the uniformity of the rainfall distribution as discussed in the previous section. It is expected that with an application to a storm with marked spatial variability, such as a localized convective storm, a substantial difference would occur between simulations based on grid-distributed versus spatially-averaged rainfall. The difference would be due to both the grid-based calculation of losses as well as the grid-based translation of rainfall excess. Hypothetical data have been used to confirm this conclusion, but data have not been available for the watershed above Tenkiller Lake for such comparisons.

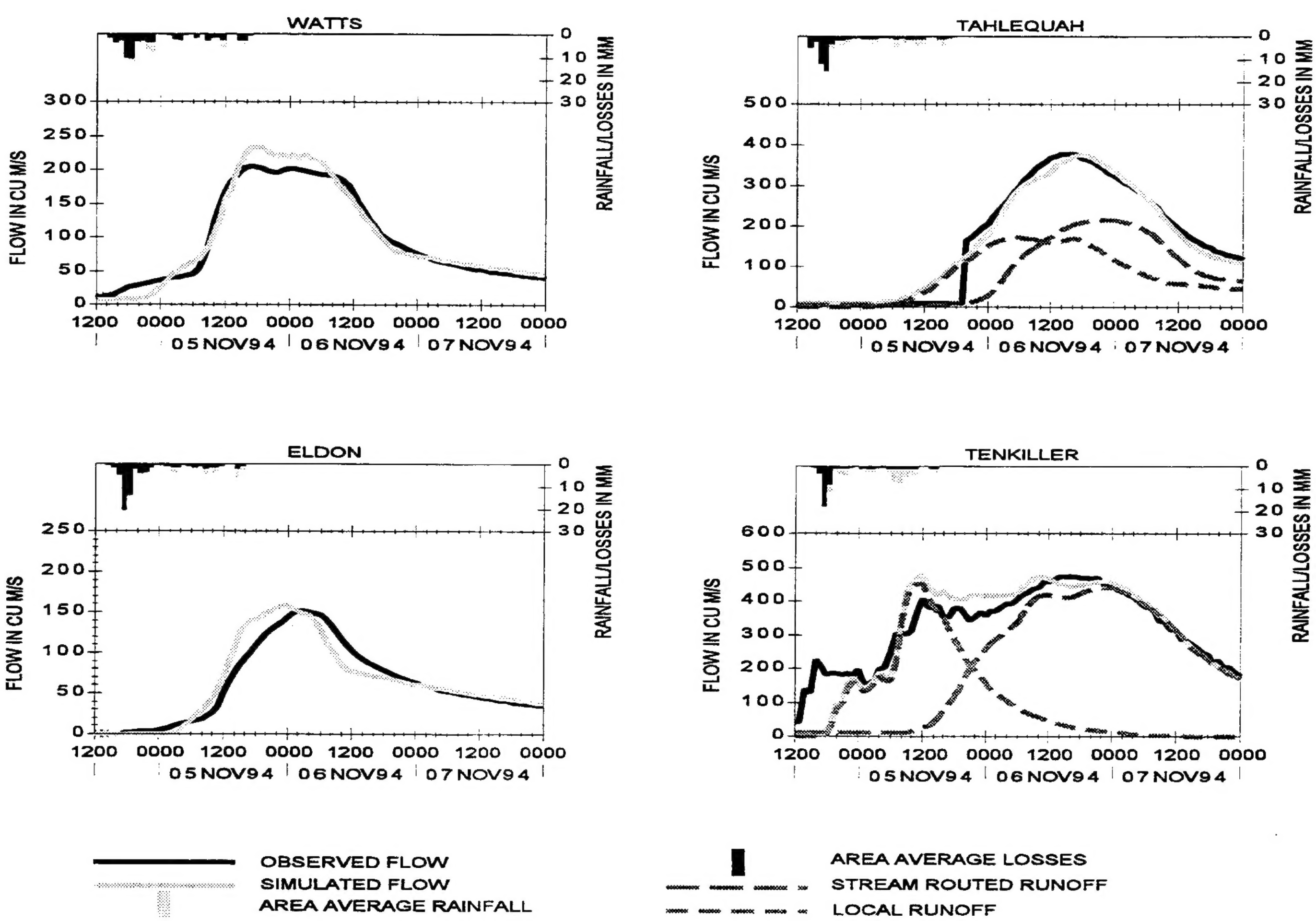

Figure 4. Modified Clark Rainfall-Runoff Simulations for the November 4-5, 1994, Storm.

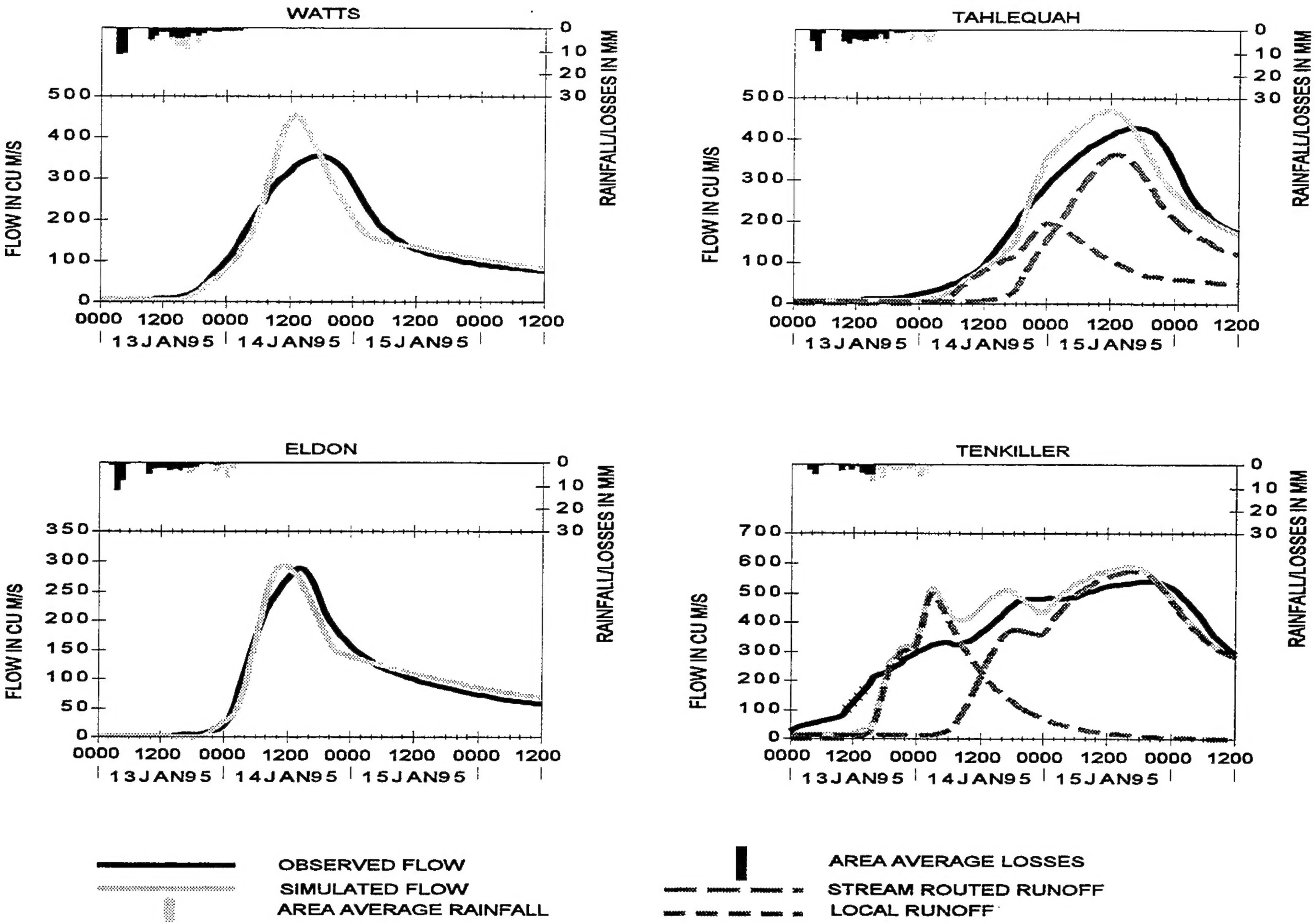

Figure 5. Modified Clark Rainfall-Runoff Simulations for the January 13-14, 1995, Storm.

CONCLUDING REMARKS

The availability of rainfall data from WSR-88D radars affords new opportunities for increasing the spatial detail with which rainfall-runoff processes are simulated. A simple method for simulating watershed runoff by using a linear transform of grid-distributed rainfall excess is described herein. Aside from cell properties (which can be obtained with GIS procedures), the data requirements for the Modified Clark method are essentially the same as for existing lumped-parameter models. The method thus provides a relatively straightforward transition to use of radar-rainfall data. As more physically based distributed models come into use, it may be useful to compare their performance, data requirements, and utility with a simpler approach such as that described herein.

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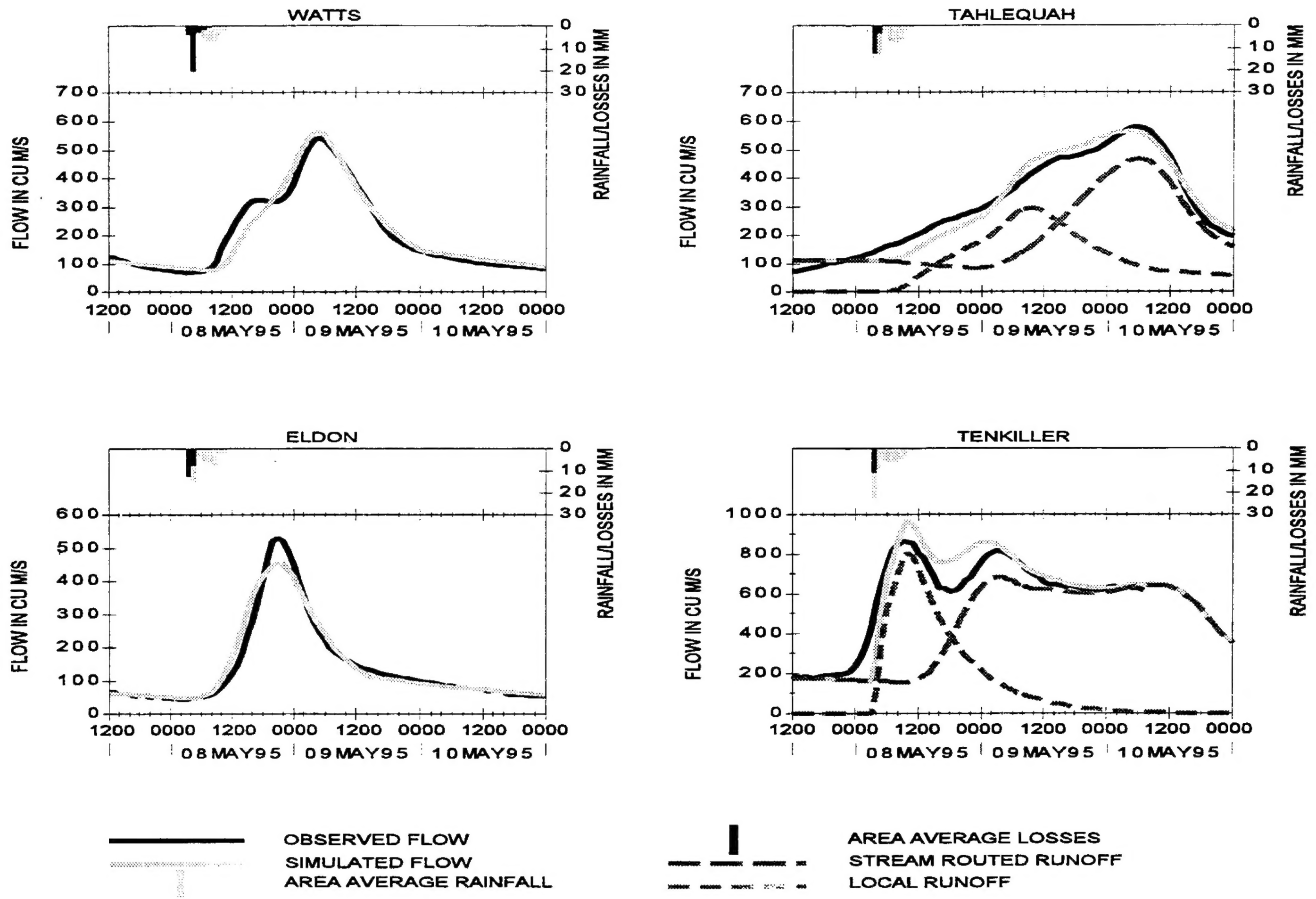

Figure 6. Modified Clark Rainfall-Runoff Simulations for the May 8, 1995, Storm.

TABLE 3. Modified Clark Model Parameters Used in Test Simulations.

		Clark Parameters		Loss Parameters		Baseflow Parameters	
Subbasin	Storm Event	Tc (hours)	R (hours)	Initial Loss (mm)	Constant Loss Rate (mm/hr)	Initial Flow (cu. m/s)	Recession Ratio*
85	November 4-5, 1994	30	15.5	62.3	1.3	1.4	1.02
	January 13-14, 1995	30	15.5	57.2	1.0	2.8	1.02
	May 8, 1995	30	15.5	17.5	0.0	0.0	1.02
86	November 4-5, 1994	24	11.6	69.9	3.6	8.5	1.02
	January 13-14, 1995	24	11.6	27.9	5.1	8.5	1.02
	May 8, 1995	24	11.6	30.2	0.0	113.0	1.02
113	November 4-5, 1994	16	9.7	92.7	1.8	1.4	1.02
	January 13-14, 1995	16	9.7	56.6	0.0	2.8	1.02
	May 8, 1995	16	9.7	21.1	0.0	65.1	1.02
127	November 4-5, 1994	1	10.0	32.0	1.5	0.0	1.00
	January 13-14, 1995	1	10.0	30.0	0.0	0.0	1.00
	May 8, 1995	1	10.0	12.7	0.0	0.0	1.00

*The ratio is that of the initial flow to the flow one hour later.

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